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Combined diversity and improved energy detection in cooperative spectrum sensing with faded reporting channels

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Abstract In this paper we evaluate the performance of cooperative spectrum sensing (CSS) where each cognitive radio (CR) employs an improved energy detector (IED) with multiple antennas and uses selection combining (SC) for detecting the primary user (PU) in noisy and faded sensing (S) channels. We derive an expression for the probability of false alarm and expressions for probability of missed detection in non-faded (AWGN) and Rayleigh faded sensing environments in terms of cumulative distribution function (CDF). Each CR transmits its decision about PU via noisy and faded reporting (R) channel to fusion center (FC). In this paper we assume that S-channels are noisy and Rayleigh faded while several cases of fading are considered for R-channels such as: (i) Hoyt (or Nakagami-*q*), (ii) Rayleigh, (iii) Rician (or Nakagami-*n*), and (iv) Weibull. A Binary Symmetric channel (BSC) with a fixed error probability (*r*) in the R-channel is also considered. The impact of fading in R-channel, S-channel and several network parameters such as IED parameter, normalized detection threshold, number of CRs, and number of antennas on missed detection and total error probability is assessed. The effects of Hoyt, Rician, and Weibull fading parameters on overall performance of IED-CSS are also highlighted.

1. Introduction

Cognitive radio (CR)[1] is a kind of intelligent wireless device, which is able to adjust its transmission parameters, such as transmit power and transmission frequency band, based on the environment (Haykin, 2005). In a CR network, ordinary wireless devices are referred to as primary users (PUs), and CRs are referred to as secondary users (SUs). The CR user

[1] Note that with the generic term cognitive radio (CR) we also refer to a secondary (or cognitive) user (SU). The context will eliminate any ambiguity.

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can use spectrum only when it does not cause interference to the PUs. Thus sensing of vacant spectrum is very important for a successful operation of CR network. However, sensing the spectrum is a hard task because of shadowing, fading, and time-varying nature of wireless channels (Cabric et al., 2004). Due to the severe multipath fading, a CR user may fail to detect the presence or the absence of the PU. The performance of a single CR user using conventional energy detector (CED) has been studied in several fading channels such as log-normal shadowing, Rayleigh, and Nakagami-m fading channels in Nallagonda et al. (2012a) and Digham et al. (2003) where the Nakagami distribution provides flexibility in describing the fading severity of the channel and considers special cases such as the well known Rayleigh fading for a certain value of the fading parameter ($m = 1$). Cooperative spectrum sensing (CSS) improves the detection performance where all CR users use identical CEDs and sense the PU via faded sensing (S) channels individually and send their sensing information in the form of 1-bit binary decisions (1 or 0) via ideal (noiseless) reporting (R) channels to fusion center (FC) Ghasemi and Sousa (2005, 2007) and Nallagonda et al. (2012b). Then, the FC employs any one of the hard decision combining fusion rules such as OR-logic, AND-logic and majority-logic fusion rules and makes a global decision about the presence or the absence of the PU. In (Quan, 2008; Ma and Li, 2007), soft decision combining fusion for cooperative sensing based on energy detection has been studied. In the case of soft decision, CR users forward the entire sensing data i.e., received energies at individual CR users to the FC without performing any local decision (1 or 0) at each CR user.

It should be noted that the channels between the PU and CR users are called sensing channels (S-channels) and the channels between the CRs and the FC are called reporting channels (R-channels). The performance of CED based CSS has also been studied in several fading channels where R-channels are assumed to be ideal (noiseless) and S-channels are considered as Hoyt (or Nakagami-q) Nallagonda et al., 2012c, Rican (or Nakagami-n) and Weibull fading channels. Hoyt distribution (Hoyt, 1947; Chandra et al., 2013; Simon and Alouini, 2004), also known as Nakagami-q distribution (q being the fading severity parameter), allows us to span the range of fading distribution from one-sided Gaussian ($q = 0$) to Rayleigh fading ($q = 1$), and is used extensively for modeling more severe than Rayleigh fading wireless links. The Weibull distribution also provides flexibility in describing the fading severity of the channel and considers special cases such as the well known Rayleigh fading for a certain value of the fading parameter (Ismail and Matalgah, 2006). The performance of single CR user based spectrum sensing (Nallagonda et al., 2011) is the best in Weibull fading channel among other channels such as Rician, Nakagami-m. Depending on the particular propagation environment (either in sensing side or reporting side) and the underlying communication scenario, several such models have been investigated. Table 1 lists the fading models along with their application environments.

However, in many practical situations R-channels may not be noiseless channels. More precisely, the wireless links between CRs and FC my experience noise and fading or shadowed. Several researchers assume that CRs report their local decisions or energy values to FC via noisy and faded channels. Particularly, in Zhao et al., 2013, both sensing and reporting

Table 1 Type of fading and Propagation environment (Chandra, 2011; Hashemi, 1993; Adawi et al., 1988).

Fading	Propagation environment
Rayleigh	Mobile systems with no line-of-sight (LoS) path, propagation of reflected and refracted paths through troposphere and ionosphere, maritime ship-to-ship communication links
Rician	LOS paths of microcellular urban and suburban land mobile, picocellular indoor, and factory environments, dominant LOS path of satellite radio links
Hoyt	Satellite links subject to strong ionospheric scintillation
Weibull	Good fit to mobile radio fading data, indoor, and outdoor environments

channels are assumed as noisy and faded. With this assumption, the author proposed filter-bank based soft decision fusion (SDF) cooperative spectrum sensing system. In Zou et al., 2011, a selective-relay based cooperative spectrum sensing scheme, assuming noisy and Rayleigh faded channels in both sensing and reporting sides, is proposed. The R-channels are considered as noisy and Rayleigh faded in Ferrari and Pagliari (2006), Chen et al., 2004, in the context of a sensor network where sensors report their decisions to FC. The performance of CSS can be improved further by utilizing an improved energy detector (IED) at each CR user, where the conventional energy detector is modified by replacing the squaring operation of the received signal amplitude with an arbitrary positive power parameter (Chen, 2010; Singh et al., 2011). The performance of CSS using IED and SC based multi antenna at each CR is analysed (Singh et al., 2012) where S-channel is considered as Rayleigh faded and R-channel is considered as binary symmetric channel (BSC) only with a fixed error probability of 'r'. However, impact of different types of fading in R-channels is not considered. In Nallagonda et al., 2012d, two cases of fading such as: (i) Rayleigh and (ii) Nakagami-m with noise are only considered in R-channel to evaluate the performance of same network as given in Singh et al. (2012).

In the present paper we consider the same detection scheme at CR level as presented in Singh et al. (2012) and Nallagonda et al. (2012d) and extend the analysis to considering three other cases of fading in the R-channel such as Hoyt, Rician, and Weibull in contrast to a simple BSC as discussed in Singh et al. (2012) and well known fading channels as discussed in Nallagonda et al. (2012d). The motivation behind considering Hoyt (Subadar and Sahu, 2011), Rician (Khatalin and Fonseka, 2006) and Weibull (Ikki and Aissa, 2011; Ivan et al., 2011) is that they represent the most general fading situations. In this paper first we derive an expression for probability of false alarm and also expressions for probability of missed detection in non-faded (AWGN) and Rayleigh faded sensing environments in terms of cumulative distribution function (CDF) using Van Trees, 1968, Eq. (41), chapter 2. It should be noted in this paper that the expressions for probability of false alarm and probability of missed detection via CDF involves multi-antenna parameter (M) in CDF only. More precisely, in this paper we consider a Rayleigh faded S-channel, and cases with several types of fading such as Hoyt, Rayleigh, Rician, and Weibull in R-channels. Missed detection and total error probabilities are selected as the key performance metric in this paper. A simulation framework has been developed in MATLAB for evaluating the performance.

Specifically our contributions in this paper are as follows:

- We derive an expression for probability of false alarm (P_f) at CR user level and also expressions for probability of missed detection (P_m) at CR user level in non-faded (AWGN) and Rayleigh faded sensing environments using Van Trees, 1968, Eq. (41), chapter 2. The analytical results based on derived expressions are validated with simulation results based on our developed simulation test bed.
- The performance of a single CR based and cooperative CR based spectrum sensing has been investigated when several cases of R-channel are considered such as BSC with a fixed error probability (r), Hoyt, Rayleigh, Rician, and Weibull fading channels while S-channel is Rayleigh faded. Impacts of different fading in R-channel and the number of cooperative CR users are also indicated on overall detection performance.
- The effects of IED parameter (p), normalized detection threshold (λ_n), and the number of antennas at each CR on sensing performance are investigated. An optimal value of 'p' and 'λ_n' are indicated when the number of CR users and number of antennas, respectively, are varied in the network.
- Performance comparison among the several hard decision combining fusion rules under noiseless (ideal case) and various fading in R-channels is also highlighted.

The rest of the paper is organized as follows. In Section 2, the system model for CSS is described. In Section 3, analytical model for evaluating the performance of CSS is presented. In Section 4, we describe the simulation model where methods for generating different fading distributions are discussed. In Section 5, simulation results are presented and commented. Finally, Section 6 concludes the paper.

2. System model

We consider a cooperative spectrum sensing (CSS) network of 'N' CR users, one primary user (PU) and one fusion centre (FC) as shown in Fig. 1. The PU and FC consists of single antenna and each CR user uses an improved energy detector (IED) and selection combining (SC) based multiple antennas (M). We assume that each CR user has an identical detection threshold (λ). A cognitive radio user makes a hard binary decision regarding the presence or absence of the PU and transmits its decision using binary phase shift keying (BPSK) modulation to the FC. As already discussed in the previous section, the sensing (S) channels are considered as noisy-Rayleigh faded channel while reporting (R) channels are considered as: (a) BSC with a fixed error probability (b) noisy-Hoyt (or Nakagami-q) faded (c) noisy-Rayleigh faded, (d) noisy-Rician (or Nakagami-n) faded, and (e) noisy-Weibull faded. In the previous section, it is already discussed that the nature of fading in S-channel or in R-channel depends on the type of environment and application. Depending on the scenario, the R-channel is considered to be affected by any one of the possible fading such as Hoyt, Rayleigh, Rician, and Weibull while S-channel is considered to be affected by Rayleigh fading only. The fading, S-channel SNR, and R-channel SNR are the main parameters of the proposed system. At the lower SNR of S-channel due to severe fading, selection diversity is invoked at CR to improve detection. Similarly, at low SNR of R-channel due to severe fading cooperative diversity is used at FC to improve detection. Thus in our scenario, we consider a moderate level of SNR at S-channel and R-channels, and a wide range of fading parameters is chosen.

The received signal at ith antenna $y_i(t)$ at each CR user can be represented as:

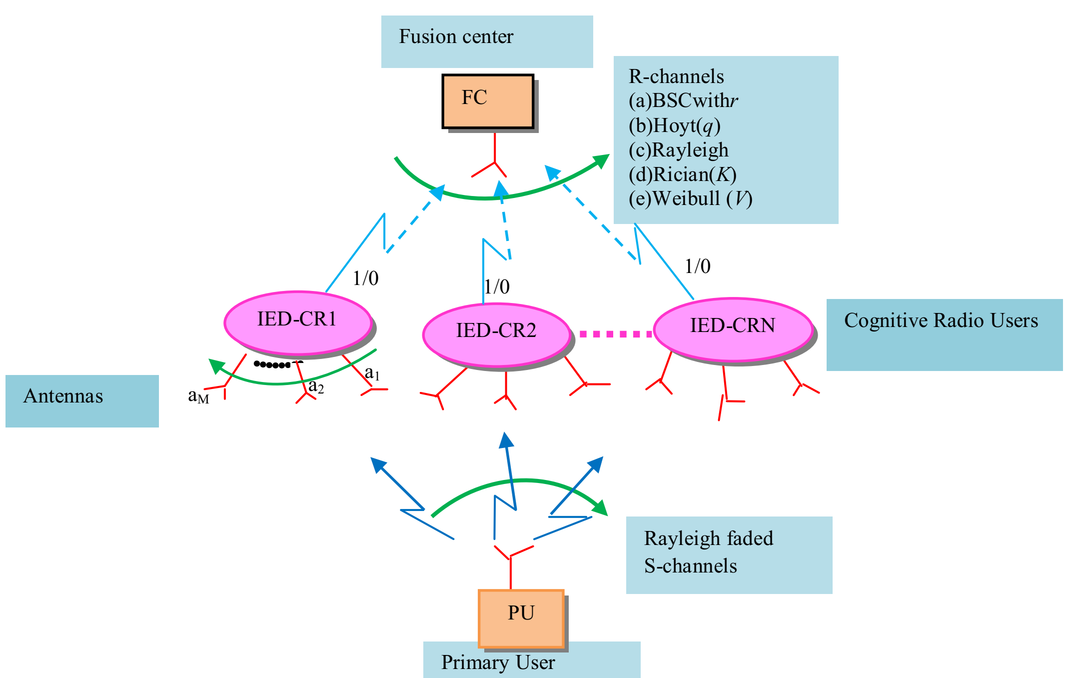

Figure 1 Proposed IED-CSS system.

$$y_i(t) = \begin{cases} n_i(t) & H_0 \\ h_i s(t) + n_i(t) & H_1 \end{cases} \tag{1}$$

where 'i' is the antenna index ($i = 1, 2, \ldots M$) at each CR user, $s(t)$ is the signal from the PU at time instant t with energy E_s and $n_i(t)$ is the noise waveform i.e. additive white Gaussian noise (AWGN). The noise $n_i(t)$ is modelled as a zero-mean circularly symmetrical complex Gaussian random process, i.e., $n_i(t) \sim CN(0, \sigma_n^2)$, where σ_n^2 is the noise variance. h_i is the Rayleigh faded S-channel coefficient at ith antenna at each CR user and is modelled as $n_i(t) \sim CN(0, \sigma_h^2)$, where $\sigma_h^2 = 1$. H_1 and H_0 are the two hypotheses associated with the presence and absence of a PU respectively. The decision statistic at the ith antenna at each CR user for deciding the presence or absence of the PU is given by Chen (2010), Singh et al. (2011, 2012), Nallagonda et al. (2012d):

$$W_i = |y_i|^p, \qquad p > 0, \tag{2}$$

where time index 't' is dropped for simplicity, p is the improved energy detector parameter. It can be seen from (2) that W_i reduces to the statistic corresponding to the conventional energy detector (CED) for $p = 2$ Digham et al. (2003) and Ghasemi and Sousa (2005, 2007).

3. Detection analysis in non-fading and fading environments

In this section, first we derive the expressions of probability of false alarm and probability of missed detection at the CR level in non faded channel and Rayleigh faded channels. Next we analyse the overall probabilities of false alarm and missed detection at FC.

3.1. Non-fading environment (i.e. AWGN channel, $h_i = 1$)

The generalized expressions for probabilities of false alarm and missed detection are given in Van Trees (1968), Eq. (41), chapter 2 as

$$P_f = \int_\lambda^\infty f_{Z|H_0}(z)dz = 1 - F_{Z|H_0}(\lambda) \tag{3}$$

$$P_m = \int_{-\infty}^\lambda f_{Z|H_1}(z)dz = F_{Z|H_1}(\lambda) \tag{4}$$

where $f_{Z|H_0}(z)$ and $f_{Z|H_1}(z)$ are conditional probability density function (PDF) of z under hypothesis H_0 and H_1, respectively.

The cumulative distribution function (CDF) of the improved energy detector can be written as (Singh et al., 2012)

$$P_{W_i}(x) = \Pr(|y_i|^p \leqslant x) \tag{5}$$

where Pr(.) denotes the probability. Each CR evaluates its decision statistic for all ($i = 1, 2, \ldots M$) antennas and uses selection combining (SC) diversity technique that outputs the maximum value out of M decision statistics evaluated for different diversity branches as $Z = \max(W_1, W_2, \ldots\ldots, W_M)$. The conditional PDF of W_i under hypothesis H_0 appears to be exponentially distributed (Singh et al., 2012) as

$$f_{W_i|H_0}(y) = \frac{2y^{(2/p)-1}}{p\sigma_n^2} \exp\left(-\frac{y^{2/p}}{\sigma_n^2}\right) \tag{6}$$

Thus, the probability that the decision statistic W_i is less than z, under hypothesis H_0 is Singh et al., 2012

$$\Pr(W_i \leqslant z|H_0) = \int_0^z f_{W_i|H_0}(y)dy = 1 - \exp\left(-\frac{z^{2/p}}{\sigma_n^2}\right) \tag{7}$$

Next we present the conditional CDF of the SC under hypothesis H_0. The conditional CDF is given by Singh et al. (2012)

$$F_{Z|H_0}(z) = \Pr[\max(W_1, W_2 \ldots\ldots\ldots, W_M) \leqslant z|H_0]$$

$$= \left[1 - \exp\left(-\frac{z^{2/p}}{\sigma_n^2}\right)\right]^M \tag{8}$$

Using the CDF of Eq. (8) we derive the conditional PDF of W_i under hypothesis H_1 in AWGN channel as

$$f_{W_i|H_1}(y)_{\text{AWGN}} = \frac{2y^{(2/p)-1}}{p\sigma_n^2} \exp\left(-\frac{y^{2/p}+E_s}{\sigma_n^2}\right) I_0\left(\frac{2y^{1/p}\sqrt{E_s}}{\sigma_n^2}\right) \tag{9}$$

Using (Nuttall, 1975), Eq. (9), the probability that the decision statistic W_i is less than z, under hypothesis H_1 in AWGN environment is

$$\Pr(W_i \leqslant z|H_1)_{\text{AWGN}} = 1 - Q\left(\sqrt{\frac{2E_s}{\sigma_n^2}}, z^{1/p}\sqrt{\frac{2}{\sigma_n^2}}\right). \tag{10}$$

where $Q(.,.)$ is the Marcum Q-function. Using (10), the conditional CDF of the SC under hypothesis H_1 in AWGN channel is

$$F_{Z|H_1}(z) = \Pr[\max(W_1, W_2 \ldots\ldots, W_M) \leqslant z|H_1]$$

$$F_{Z|H_1}(z)_{\text{AWGN}} = \left[1 - Q\left(\sqrt{\frac{2E_s}{\sigma_n^2}}, z^{1/p}\sqrt{\frac{2}{\sigma_n^2}}\right)\right]^M \tag{11}$$

The output of the SC is now applied to a one-bit hard detector which takes decision about the presence or absence of a PU (Singh et al., 2012 and Nallagonda et al., 2012d):

$$\begin{aligned} &Z > \lambda \quad 1, \\ &Z < \lambda \quad 0. \end{aligned} \tag{12}$$

where binary bits '1' and '0' correspond to the decision about the presence and absence of the PU, respectively.

From (2), it is observed that for a small and large value of p, the corresponding values of W obtained at CR are lower and higher. In order to take a proper decision about PU at that CR, the detection threshold (λ) is set in such way that W should be compared with a reasonable value of λ. Thus it is justified to express the detection threshold in terms of IED parameter p. Depending on p amount of noise captured by IED which varies the W, we need to normalize the threshold of comparison with respect to noise power captured by IED (σ_n^p). Thus normalized threshold $\lambda_\text{n} = \lambda/\sigma_n^p$ is used where λ can obtained as

$$\lambda = \lambda_\text{n}\sigma_n^p \tag{13}$$

All CRs are assumed to have the same detection threshold. From (12), (8) and (3), the probability of false alarm P_f in each CR can be expressed as

$$P_f = 1 - \left[1 - \exp\left(-\frac{\lambda^{2/p}}{\sigma_n^2}\right)\right]^M. \tag{14}$$

It should be noted that the P_f expression in (14) via CDF involves multi-antenna parameter (M) in CDF i.e. $F_{Z|H_0}(\lambda)$ only. The CDF $F_{Z|H_0}(\lambda)$ can be obtained using (Van Trees, 1968), Eq. (41), chapter 2 as:

$$F_{Z|H_0}(\lambda) = \left[1 - \exp\left(-\frac{\lambda^{2/p}}{\sigma_n^2}\right)\right]^M. \tag{15}$$

Similarly, from (12), (11) and (4), the probability of missed detection in AWGN channel, $P_{m_{\text{AWGN}}}$ can be obtained as

$$P_{m_{\text{AWGN}}} = \left[1 - Q\left(\sqrt{\frac{2E_s}{\sigma_n^2}}, \lambda^{1/p}\sqrt{\frac{2}{\sigma_n^2}}\right)\right]^M. \tag{16}$$

As expected, P_f is same for any fading environment since under H_0 there is no PU signal is present.

3.2. Rayleigh fading environment

For Rayleigh faded environment, the circularly symmetrical complex Gaussian channel gain implying Rayleigh fading $|h_i| = |h_I + jh_Q|$; $h_{I,Q} \sim N(0, \sigma_h^2/2)$ where $\sigma_h^2 = 1$. The received signal under H_1 can be expressed as sum of real and imaginary components i.e.

$$y_i = (\sqrt{E_s}h_I + n_I) + j(\sqrt{E_s}h_Q + n_Q)$$

$$= X_1 + jX_2 \tag{17}$$

where $X_{1,2} \sim N(0, (E_s\sigma_h^2 + \sigma_n^2)/2)$.

We now obtain the conditional PDF of W_i under H_1 in Rayleigh faded environment (Singh et al., 2012)

$$f_{W_i|H_1}(y)_{\text{Rayl}} = \frac{2y^{(2/p)-1}}{p(E_s\sigma_h^2 + \sigma_n^2)} \exp\left(-\frac{y^{2/p}}{E_s\sigma_h^2 + \sigma_n^2}\right) \tag{18}$$

From (18), the probability that the decision statistic W_i is less than z under hypothesis H_1 is given by Singh et al. (2012)

$$\Pr(W_i \leqslant z|H_1)_{\text{Rayl}} = 1 - \exp\left(-\frac{z^{2/p}}{E_s\sigma_h^2 + \sigma_n^2}\right) \tag{19}$$

Using (19), the conditional CDF of the SC under hypothesis H_1 in Rayleigh faded environment is (Singh et al., 2012)

$$F_{Z|H_1}(z)_{\text{Rayl}} = \left[1 - \exp\left(-\frac{z^{2/p}}{E_s\sigma_h^2 + \sigma_n^2}\right)\right]^M \tag{20}$$

From (20), (12) and (4), the probability of missed detection in Rayleigh faded environment, $P_{m_{\text{Rayl}}}$ can be obtained as

$$P_{m_{\text{Rayl}}} = \left[1 - \exp\left(-\frac{\lambda^{2/p}}{\sigma_n^2(1+\bar{\gamma})}\right)\right]^M \tag{21}$$

where $\bar{\gamma} = E_s\sigma_h^2/\sigma_n^2$ is the average signal to noise ratio (SNR) of the link between a PU and a CR. It should be noted that the P_{mRayl} expression in (20) via CDF involves multi-antenna parameter (M) in CDF i.e. $F_{Z|H_1}(\lambda)$ only. The CDF $F_{Z|H_1}(\lambda)$ can be obtained using (Van Trees, 1968, Eq. (41), chapter 2) as:

$$F_{Z|H_1}(\lambda) = \left[1 - \exp\left(-\frac{\lambda^{\frac{2}{p}}}{\sigma_n^2(1+\bar{\gamma})}\right)\right]^M \tag{22}$$

3.3. Q_m and Q_f analysis without fading in R-channel

Let N denote the number of CR users sensing the PU. Each CR user makes its own local decision regarding the presence or absence of PU (i.e. H_1 or H_0), and forwards the binary decision (1 or 0) to FC for data fusion. The overall probability of false alarm (Q_f) and the probability of missed detection (Q_m) under OR-logic fusion at FC where the R-channel is a BSC with 'r' as fixed error probability (Singh et al., 2012; Nallagonda et al., 2012d):

$$Q_f = 1 - [(1-P_f)(1-r) + rP_f]^N, \tag{23}$$

$$Q_m = [P_m(1-r) + r(1-P_m)]^N. \tag{24}$$

where P_m and P_f are the pair of missed and false alarm probabilities at each CR user following Eqs. (16), (21) and (14), respectively.

3.4. Q_m and Q_f analysis with fading in R-channel

In case of fading in R-channel, the received signal at the FC from kth CR via R-channel is (Nallagonda et al., 2012e):

$$\bar{y}_k = m_k h_k + n_k; \quad k \in \{1, 2, ..., N\} \tag{25}$$

where h_k is the kth R-channel fading coefficient, and noise (n_k) is zero-mean circularly symmetrical complex Gaussian random process i.e. $n_k \sim CN(0, \sigma_n^2)$; $\sigma_n^2 = E_b/(2\bar{\gamma}_R)$, where E_b is energy per bit which is equal to 1, and $\bar{\gamma}_R$ is the average R-channel SNR. The BPSK message signal (m_k) depends on the decision taken at a CR user i.e., $m_k \in (+\sqrt{E_b}, -\sqrt{E_b})$ where $+\sqrt{E_b}$ indicates that the PU is present and $-\sqrt{E_b}$ indicates that the PU is absent. Since the R-channel is noisy and affected by fading, a decision received by the FC might differ from the one sent by the corresponding CR user. At FC there is an identical threshold device for each CR user where threshold is set as '0'. If $\bar{y}_k > 0$ then FC takes a decision (u_k) in favour of H_1 otherwise it decides in favour of H_0 following (Nallagonda et al., 2012e):

$$u_k = \begin{cases} 1 & \text{if the received decision is } H_1 \\ 0 & \text{if the received decision is } H_0 \end{cases} \tag{26}$$

where $k \in \{1, 2, \ldots, N\}$. The FC finally makes a global decision 'Λ' according to a fusion rule $\Lambda = \Gamma(u_1, u_2 ... u_N)$, where a general OR-logic fusion rule can be expressed as:

$$\Lambda = \Gamma(u_1, u_2 \ldots, u_N) = \begin{cases} H_1 & \text{if} \quad \sum_{k=1}^{N} u_k \geqslant 1 \\ H_0 & \text{if} \quad \sum_{k=1}^{N} u_k < 1. \end{cases} \tag{27}$$

In other words, if the number of decisions in favour of H_1 is greater than or equal to 1, then the FC takes a global decision in favour of H_1, otherwise in favour of H_0.

Using Eq. (27), the general AND-logic fusion rule can be expressed as:

$$\Lambda = \Gamma(u_1, u_2 \ldots, u_N) = \begin{cases} H_1 & \text{if} \quad \sum_{k=1}^{N} u_k = N \\ H_0 & \text{if} \quad \sum_{k=1}^{N} u_k < N. \end{cases} \tag{28}$$

In other words, if the number of decisions in favour of H_1 is equal to N, then FC takes a global decision in favour of H_1, otherwise in favour of H_1.

Similarly, the majority-like expression (Nallagonda et al., 2012e) can be expressed as:

$$\Lambda = \Gamma(u_1, u_2 \ldots, u_N) = \begin{cases} H_1 & \text{if} \quad \sum_{k=1}^{N} u_k > \frac{N}{2} \\ H_0 & \text{if} \quad \sum_{k=1}^{N} u_k < \frac{N}{2} \\ H_0 \text{ or } H_1 & \text{if} \quad \sum_{k=1}^{N} u_k = \frac{N}{2} \end{cases} \tag{29}$$

In other words, if the number of decisions in favour of H_1 is larger than the number of decisions in favour of H_0, the FC takes a global decision in favour of H_1 and vice versa if the number of decisions in favour of H_1 is equal to the number of decisions in favour of H_0. The FC flips a fair coin and takes a decision in favour of either H_1 or H_0. Q_f and $Q_m = 1 - Q_d$ could be obtained under OR-logic, AND-logic and majority-logic fusion rules by using Eqs. (27), (28) and (29), respectively, over a number of simulations in case of fading. The different fading channels (such as Hoyt, Rayleigh, Rician, and Weibull) and their generation will be studied in the next section. The total error rate is given by Singh et al. (2012):

$$Z(p, \lambda, N) \cong Q_f + Q_m. \tag{30}$$

4. Simulation model

The simulation test bed is developed in MATLAB. The simulation is carried out according to the following steps to verify the analytical framework introduced in the previous section. The S-channel is considered as noisy and Rayleigh faded in entire simulation study.

4.1. Q_m and Q_f simulation in Hoyt, Rayleigh, Rician, and Weibull faded R- channels

(1) Equally likely hypothesis $H \in \{H_0, H_1\}$ and PU signal, $s(t)$ with bits 1, 0 are generated using a uniform random variable generator.
(2) Complex Gaussian noise signal, $n_i(t)$ and Rayleigh faded S-channel coefficients (h_i) at ith antenna of a CR user are generated using two Gaussian Random variables.
(3) The received signal at ith antenna of a CR user under hypothesis H_1 is $y(t) = h_i s(t) + n_i(t)$, under hypothesis H_0 is $y(t) = n_i(t)$.
(4) The decision statistic (energy of received signal amplitude) at i-th antenna W_i is evaluated according to Eq. (2) for a given value of IED parameter.
(5) Steps from 2 to 4 are repeated for 'M' number of antennas ($i = 1, 2, \ldots M$), then select the maximum value of W_i using selection combining (SC).
(6) Detection threshold (λ) can be obtained from Eq. (13) for fixed values of p, σ_n and λ_n.
(7) If the estimated value of 'W_i' from step 5 is greater than λ, then the binary decision is '1' which indicates that the PU is present. Otherwise the binary decision is '0' which indicates that the PU is absent.
(8) Steps 1–7 have been repeated for N number of CRs.
(9) The received signal at the FC from k^{th} CR user is $\bar{y}_k = m_k h_k + n_k$ (according to Eq. (25)), where n_k is the complex Gaussian noise in the R-channel, and h_k is the R-channel faded coefficient. Different fading scenarios have been considered in the R-channel such as Hoyt (q), Rayleigh, Rician (K), and Weibull (V) to evaluate the performance of the proposed IED-CSS. The method of generating different R-channel fading coefficients is given in Table 2.
(10) If Real ($\bar{y}_k > 0$) for the kth CR user, a counter (u_k) according to Eq. (26) is incremented. Initially we define the counter (u_k) and set it to zero. This step is repeated for N CR users i.e. $k = 1, 2, \ldots N$.
(11) Using Eqs. (27), (28), and (29), the average probabilities of missed detection and false alarm can be estimated under OR-logic fusion, AND logic fusion, and majority-logic fusions respectively, over a large number of simulations.

4.2. Q_m and Q_f simulation in binary symmetric channel (BSC) with $r = 0.001$

1) We follow the steps from 1 to 8 as given in Subsection 4.1 of Section 4.
2) The signal at FC from the kth CR user is $\bar{y}_k = m_k + n_k$ where 'm_k' is local decision of the kth CR user in the form of binary phase shift keying (BPSK) and n_k is the noise evaluated from $r = Q(\sqrt{2\bar{\gamma}_R})$.
3) Now we follow the steps from 10 to 11 as given in Subsection 4.1 of Section 4 (Fig. 2).

5. Results and discussions

Table 3 shows the important network parameters used in the simulation study. The S-channel is considered as noisy and Rayleigh faded in entire simulation study.

In Fig. 3, the performance of a single CR user based spectrum sensing is shown for different number of antennas (M) and various values of normalized detection threshold (λ_n).

Table 2 Type of fading and Generation of h_k.

Type of fading Coefficient (h_k)	Generation of h_k
Hoyt (parameter, q)	$X \sim N(0, q^2/(1+q^2))$; $Y \sim N(0, 1/(1+q^2))$; $h_k = \sqrt{X^2 + Y^2}$
Rayleigh	$X \sim N(0, 1/2)$; $Y \sim N(0, 1/2)$; $h_k = \sqrt{X^2 + Y^2}$
Rician (parameter, K)	$X \sim N(s', \sigma^2)$; $Y \sim N(0, \sigma^2)$; $h_k = \sqrt{X^2 + Y^2}$ where $s' = \sqrt{K/(1+K)}$ and $\sigma = 1/\sqrt{2(1+K)}$
Weibull (parameter, V)	$X \sim N(0, 1/2)$; $Y \sim N(0, 1/2)$; $h_k = (X^2 + Y^2)^{2/V}$

where $N(\mu, \sigma^2)$ is a Gaussian variate with mean μ and variance σ^2.

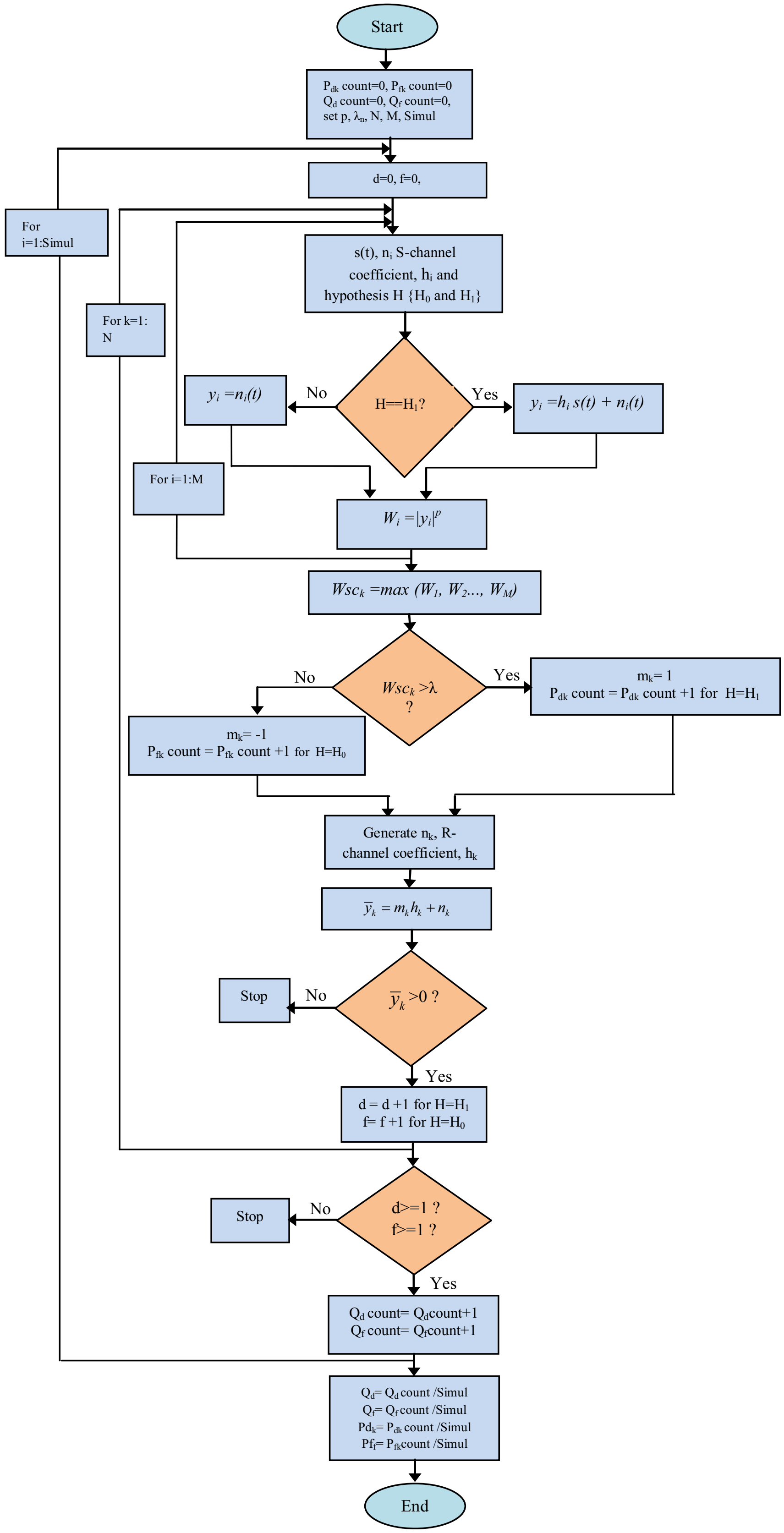

Figure 2 Flow chart of simulation process.

Table 3 Network Parameters and Values.

Parameter	Values
Number of cognitive radios (N)	1, 2, and 3
Average S – channel SNR $\bar{\gamma}_s$	10 dB
Average R – channel SNR $\bar{\gamma}_R$	10 dB
Error probability for BSC (r)	0.1 and 0.001
IED parameter (p)	1 to 10
Number of antennas (M)	2, 3 and 4
Normalized threshold (λ_n)	30
Hoyt fading parameter, q	q = 0.25, 0.5 and 1
Rician fading parameter, K	K = 0, 2 and 5
Weibull fading parameter, V	V = 2, 4 and 6

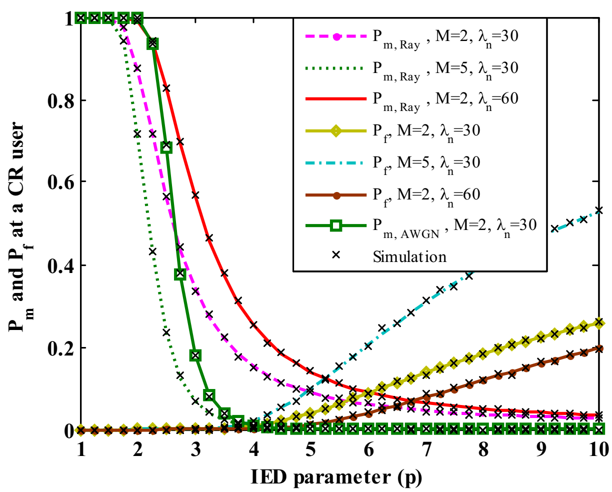

Figure 3 Performance of a single CR user in AWGN and Rayleigh fading channel for various values of M and λ_n ($\bar{\gamma}_s = 10$ dB).

The performance in terms of probability of false alarm (P_f) and probability of missed detection (P_m) of single CR user for different values of p has been evaluated in AWGN channel as well as in Rayleigh fading channel. It is seen that as p and M increase, P_m decreases and P_f increases for a particular value of λ_n. We find that P_m is very high and P_f is very low for $p = 2$ (CED with any value of M) in both AWGN and Rayleigh channels. As p increases from 2 to 10, P_m decreases rapidly, and specifically for $p = 3.75$ and $M = 5$, values of both P_m and P_f reaches to very low value (nearly zero) in Rayleigh channel. This is a great advantage of IED as compared to CED. The value of p, at which, both P_m and P_f reaches to very low value is called an optimum p. We found that an optimum value of p is 3.75 for Rayleigh case with $M = 5$. The effects of normalized detection threshold on both P_m and P_f is also shown. As λ_n increases, P_m increases and P_f decreases for a particular value of M in Rayleigh channel. This is due to the fact that increase in λ_n causes increase in λ according to Eq. (13) which leads to decrease in the probability of detection P_d (corresponding P_m $(1 - P_d)$ increases) under hypothesis H_1 as well as P_f under hypothesis H_0. Simulation results are also presented in this figure to validate our analytical framework presented in system model (Section 2).

Fig. 4 shows the comparative performance of several hard decision fusion rules on probability of detection (Q_d) at FC vs. the average S-channel SNR for 5 CR users under Rayleigh faded environment. The R-channel is assumed as ideal (or noiseless) for this figure. Excellent performance improvement for CSS has been observed with increasing average S-channel SNR for all fusion rules ($p = 4$, $M = 2$). Higher values of Q_d are obtained with OR fusion rule as compared to other fusion rules such as AND rule and majority rule as SNR increases from low value (−15 dB) to high value (20 dB). For a particular value of average SNR, 4 dB, Q_d is 0.9, 0.28 and 0 for the OR rule, AND rule and majority rule, respectively. The OR fusion rule outperforms the AND rule and majority rule in terms of probability of detection. The performance comparison between CED ($p = 2$ and $M = 2$) and IED ($p = 4$ and $M = 2$) is also shown in this figure. The curve

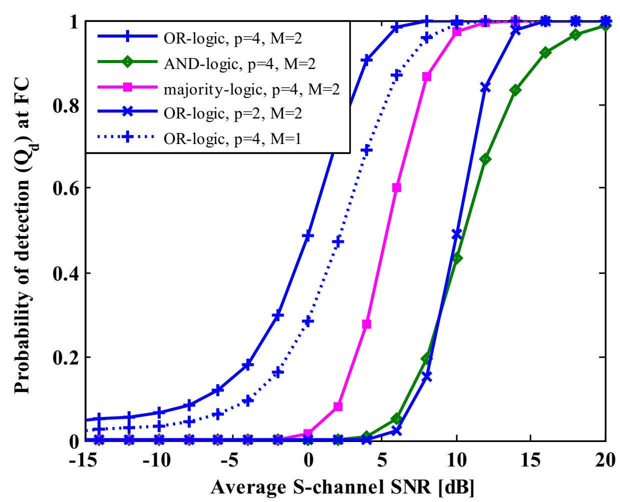

Figure 4 Performance of IED-CSS via Q_d versus average S-channel SNR in Rayleigh fading channel for various hard decision fusion rules, different values of p and M (R-channel is considered as an ideal (noiseless) channel for this figure, $N = 5$ and $\lambda_n = 30$).

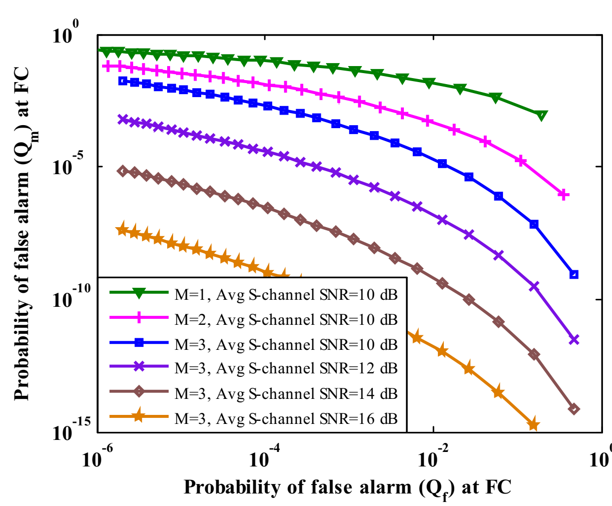

Figure 5 Complementary receiver operating characteristics (Q_m vs. Q_f) curves for various values of M and average S-channel SNR in Rayleigh fading channel, R-channel is considered as an ideal (noiseless) channel for this figure, with OR rule, $N = 5$, $p = 4$, and $\lambda_n = 5 - 350$.

for the case of IED with no SC diversity ($p = 4$ and $M = 1$) is also shown for comparison purpose.

Fig. 5 shows complementary ROC (Q_m vs. Q_f) curves for several values of average S-channel SNR and different number of antennas (M) under Rayleigh fading channel. The R-channel is assumed as ideal (or noiseless) for this figure. The OR fusion rule is considered at FC to fuse the decisions received from individual CRs. The probability of missed detection (Q_m) at FC is shown as a decreasing function of probability of the missed detection (Q_m) at FC. We observe that as average S-channel SNR and number of antennas of each CR user increase the Q_m at FC decreases. More precisely, the higher S-channel SNR increases the detection probability (P_d) at CR user so that Q_m reduces at FC. For example, for $M = 3$ and $Q_f = 1 \times 10^{-4}$, Q_m decreases from 1×10^{-3} to 1×10^{-9} as average S-channel SNR increases from 10 dB to 16 dB. The Q_m can also be reduced by increasing the number of antennas at each CR user due to the fact that performance of SC diversity combiner improves with increase in number of antennas at each CR user. For example, for average S-channel SNR = 10 dB and $Q_f = 1 \times 10^{-4}$, Q_m decreases from 1×10^{-1} to 1×10^{-3} as M increases from 1(no diversity case) to 3 (with SC diversity). The CSS with SC diversity outperforms the CSS without diversity for the same value of average S-channel SNR.

Figs. 6 and 7 show the impacts of fading in R-channels on missed detection performance of proposed IED-CSS system. The sensing (S) channel is considered as noisy and Rayleigh faded for both figures. In Fig. 6, the effects of channels such as BSC with fixed error probability $r = 0.001$, noisy-Hoyt fading ($q = 0.25$) and noisy-Rayleigh fading in reporting (R) channel are shown. Similarly, in Fig. 7, effects of other two types fading environments in R-channel such as noisy-Rician ($K = 2$) fading and noisy-Weibull ($V = 4$) fading are shown. In both Figs. 6 and 7, the performance of several hard decision fusion rules such as OR rule, AND rule and majority rules is investigated under different fading cases in R-channel. As in Fig. 4, we observe from these figures that performance of proposed IED-CSS system with OR fusion rule is better than that of any other fusion rules such as AND rule and majority rules. We also observe that a constant floor appears in missed detection with OR fusion rule in both the figures after a certain larger value of IED parameter p. This is due to the fact that under noise and fading in R-channel, FC receives decisions from all CR users with an equal error which means that decisions sent by all CR users to FC have equal probability of getting flipped. As FC is utilizing a OR fusion, it achieves a floor in the missed detection performance at a certain value of p i.e. no further improvement in detection performance is obtained by increasing value of p beyond this. It is observed from the Fig. 6 that the performance of IED-CSS guarantees the best in Rayleigh faded environment than the performance in Hoyt faded environment. It is also observed from the Fig. 7 that the performance of proposed IED-CSS system in noisy-Weibull faded environment is better than the performance in noisy-Rician faded environment for the chosen fading parameters.

In Fig. 8, the total error probability ($Q_m + Q_f$) versus IED parameter (p) for the case of R-channel; BSC with fixed error probability r is shown. The results based on simulation test bed and derived expressions are shown. Three values of N, namely 1, 3, and 8; two values of M namely 2 and 5; two values of r namely 0.001 and 0.1 are considered. The normalized detection threshold (λ_n), average S-channel and average R-channel SNR are considered as 30, 10 dB and 10 dB, respectively. The S-channel is considered as noisy and Rayleigh faded. We observe that the total error probability initially decreases with increases in the value 'p' and increases next with further increases in the value of p. Similar behaviour is also observed in case of variation of r, M, and N. Due to increase in the value of p, the detection threshold according to Eq. (13) decreases so that there is a chance of getting higher probabilities of false alarm at a CR user (P_f) and at FC (Q_f), which leads to increase in total error probability. Similarly, when the number of CR

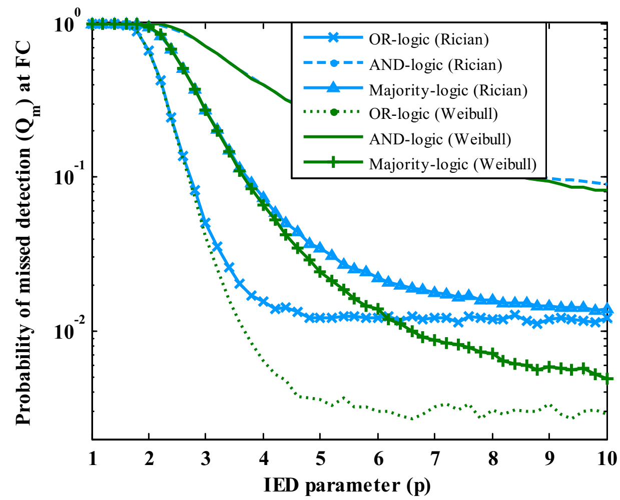

Figure 7 Performance of proposed IED-CSS with different hard decision fusion rules for two cases of R-channel; noisy-Rician ($K = 2$) and noisy-Weibull ($V = 4$) faded (S-channel is noisy-Rayleigh faded, $N = 3$, $M = 2$, $\lambda_n = 30$, average S-channel SNR = 10 dB, and average R-channel SNR = 10 dB).

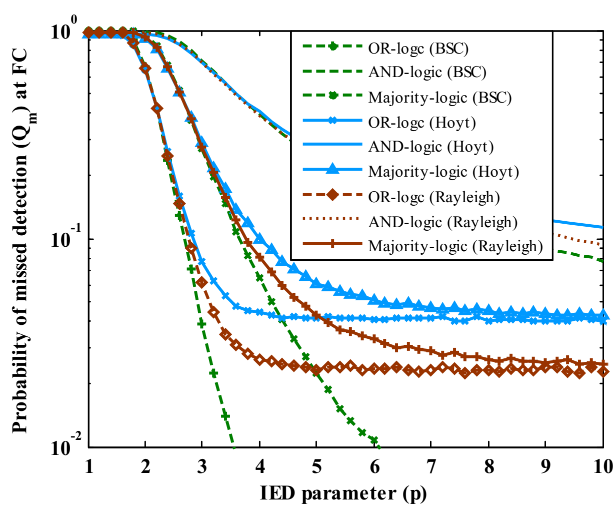

Figure 6 Performance of proposed IED-CSS with different hard decision fusion rules for two cases of R-channel; BSC with fixed error probability $r = 0.001$, noisy-Hoyt ($q = 0.25$) and noisy-Rayleigh faded (S-channel is noisy-Rayleigh faded, $N = 3$, $M = 2$, $\lambda_n = 30$, average S-channel SNR = 10 dB, and average R-channel SNRs = 10 dB).

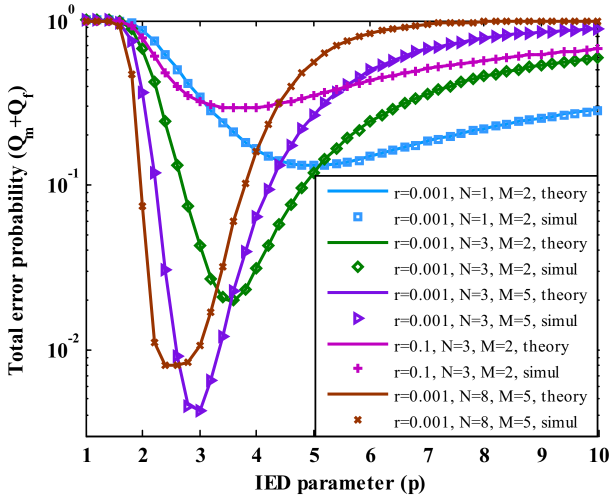

Figure 8 Total error probability ($Q_m + Q_f$) versus IED parameter (p) for several values of r, M and N; considering R-channels are BSC with fixed error probability (r), OR rule, average S-channel SNR = 10 dB, and $\lambda_n = 30$.

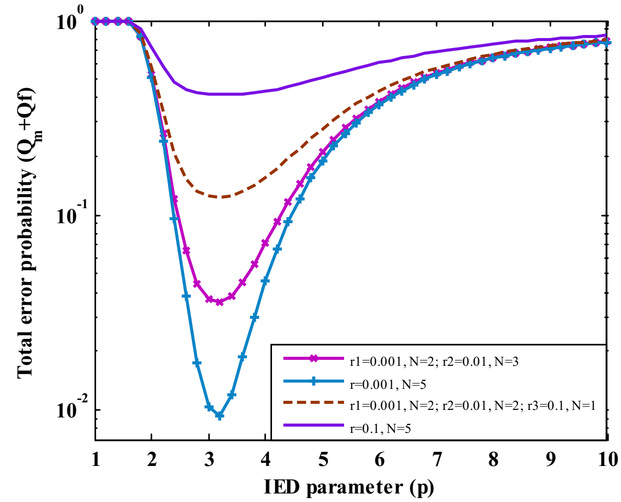

Figure 8a Total error probability ($Q_m + Q_f$) versus IED parameter (p). Different values of r for different group of CRs are considered for fixed total number of CRs ($N = 5$), OR rule, average S-channel SNR = 10 dB, $M = 2$, and $\lambda_n = 30$.

users in the network increases, and considering OR logic fusion at FC, the probability of false alarm increases which in turn increases in total error probability. It can be seen from Fig. 8 that there exists an optimum value of p for which the total error probability is minimum. This optimum value of p depends on value of r, M, and N i.e., it is different for different values of r, M, and N. For example, the optimum value of 'p' is 5.2 for $r = 0.001$, $N = 1$, and $M = 2$; 3.6 for $r = 0.001$, $N = 3$ and $M = 2$; 3 for $r = 0.001$, $N = 3$ and $M = 5$; 3.8 for $r = 0.1$, $N = 3$ and $M = 2$. We observe that when N increases (for example form $N = 1$ to $N = 3$) the total error probability decreases at a significant level. For a large value of N, say $N = 8$, the optimum threshold shifts towards the origin. This means that optimal value of p is reduced to $p = 2.4$ but total error probability is not decreased at significant level as compared to the network with $N = 3$ and $M = 5$. This is due to the fact that some CRs experience severe effect of noise in R-channels. The same behaviour, i.e. at higher value of N where the total error is not decreased at a satisfactory level can also be observed in Singh et al. (2011).

The proposed IED-CSS outperforms the single CR based spectrum sensing ($N = 1$) in noisy R-channels. The performance of CSS can be improved further by increasing the number of antennas at each CR user. It is seen that performance of CSS degrades with increase in value of error probability r in R-channel.

We also observe that the simulation results based on our simulation test bed (presented in Section 4) matches exactly with theoretical results based on derived analytical expressions (presented in Section 3) under similar conditions which validates our simulation test bed.

For simplicity, in Fig. 8, we assume that the channels connecting all CR users with FC (R-channels) are modelled with the same channel error probability (r). Though, our model and analysis are well applicable to the scenario where CRs have different R-channel qualities in terms of channel error probability. If the CRs are sufficiently far apart, their R-channels may be of different quality. To capture such cases,

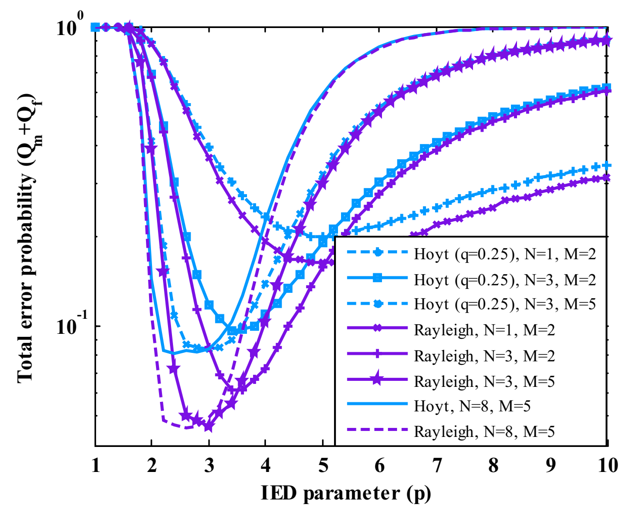

Figure 9 Total error probability ($Q_m + Q_f$) versus IED parameter (p) for several values of M and N; considering R-channels are (a) noisy-Hoyt ($q = 0.25$) and (b) noisy-Rayleigh faded environments, with OR rule, average S-channel and average R-channel SNR = 10 dB, and $\lambda_n = 30$.

in Fig. 8a, we consider a group of CRs with channel error probability r_1, and another set of CRs with probability r_2.

In practice, the CRs may have random motion. In such cases, the R-channels of CRs may be time varying. However, our present model considers a stationary scenario. This may be thought of snapshot of the scenario where the CRs remain stationary till the final decision at FC is drawn.

In Figs. 9 and 10, the total error probability ($Q_m + Q_f$) is shown as a function of IED parameter (p) for case of R-channels; noisy-Hoyt ($q = 0.25$), noisy-Rayleigh, noisy-Rician ($K = 2$) and noisy-Weibull ($V = 4$) faded. Three values of N, namely 1, 3, and 8; two values of M namely 2 and 5 are considered in both the figures. The normalized detection

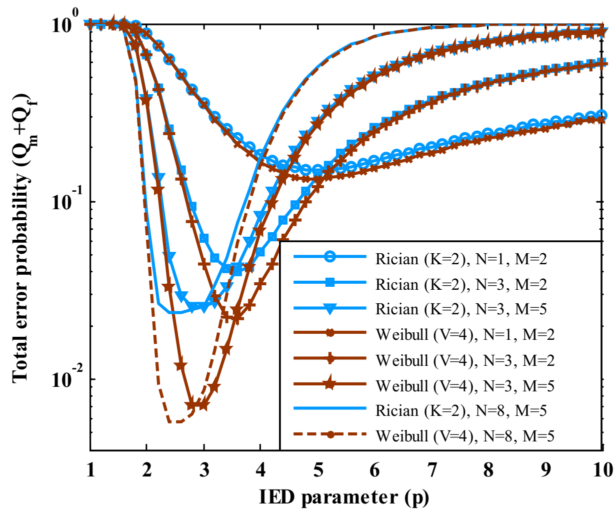

Figure 10 Total error probability ($Q_m + Q_f$) versus IED parameter (p) for several values of M and N; considering R-channels as (a) noisy-Rician ($K = 2$) and (b) noisy-Weibull ($V = 4$) faded environments, OR rule, average S-channel SNR = 10 dB, and average R-channel SNR = 10 dB, and $\lambda_n = 30$.

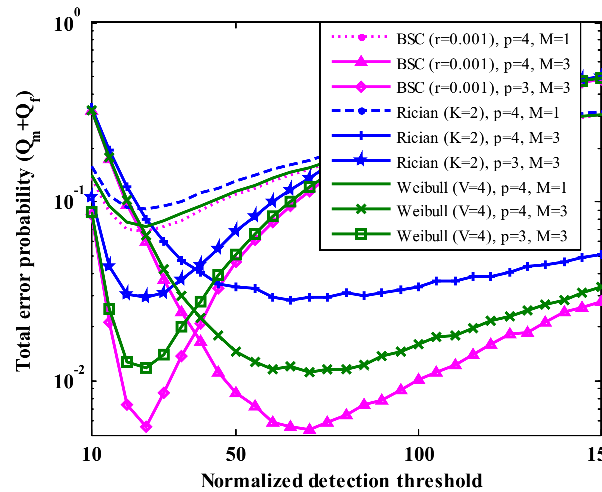

Figure 12 Total error probability ($Q_m + Q_f$) versus normalized detection threshold (λ_n) for different values of p, and M; considering R-channels are (a) BSC with $r = 0.001$, (b) noisy-Rician ($K = 2$) and (c) noisy-Weibull ($V = 4$) faded environments, with OR rule, $N = 3$, average S-channel SNR = 10 dB and average R-channel SNR = 10 dB.

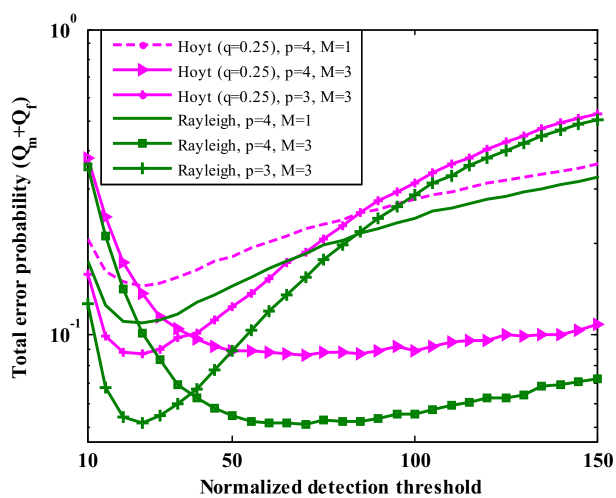

Figure 11 Total error probability ($Q_m + Q_f$) versus normalized detection threshold (λ_n) for different values of p, and M; considering R-channels are (a) noisy-Hoyt ($q = 0.25$) (b) and noisy-Rayleigh faded environments, OR rule, $N = 3$, average S-channel and average R-channel SNR = 10 dB.

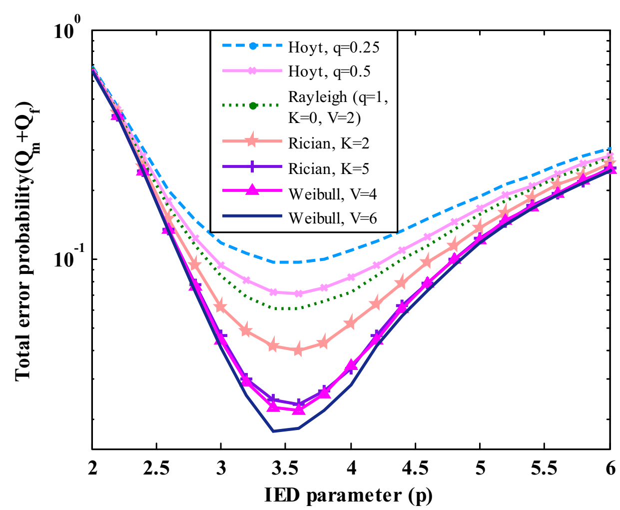

Figure 13 Impact of fading parameters on total error performance of proposed IED-CSS (OR rule, $N = 3$, M = 2, $\lambda_n = 30$, S-channel SNR = 10 dB, and R-channel SNR = 10 dB).

threshold (λ_n), average S-channel and average R-channel SNR are considered as 30, 10 dB and 10 dB, respectively. S-channel is considered as noisy and Rayleigh faded. As in Fig. 8, we also observe from these figures that the total error probability initially decreases with increase in the value 'p' and increases next with further increases in the value of p. A similar behaviour is also observed in case of variation of M, N and type of fading. It can also be seen from these figures that there exists an optimum value of p for which the total error probability is minimum. We observe that fusing the decisions of different CR users cancels the effect of fading on the detection performance effectively. Moreover, with an increase in N, Q_m decreases for a given level of p and M. The proposed IED-CSS outperforms the single CR user based spectrum sensing ($N = 1$) in all types of faded R-channels. The performance of CSS can also be improved further by increasing the number of antennas at each CR user. It is observed from Fig. 9 that the performance of IED-CSS again guarantees the best in Rayleigh faded environment than the performance in Hoyt faded environment. As in Fig. 7, it is also observed from the Fig. 10 that the performance of proposed IED-CSS system in noisy-Weibull faded environment is better than the performance in noisy-Rician faded environment for the chosen fading parameters. In both Figs. 9 and 10, it is observed that for a large value of N, ($N = 8$), the optimum threshold shifts towards the origin.

The total error probability reduces at significant level as the CRs experience less effect of noisy and fading in R-channels.

In Figs. 11 and 12, the total error probability ($Q_m + Q_f$) is shown as a function of the normalized detection threshold (λ_n) for various values p and M. Two values of p namely 3 and 4; two different values of M namely 1 and 3 are considered for both figures. In Fig. 11 the effects of noisy-Hoyt ($q = 0.25$) and noisy-Rayleigh faded R-channel; in Fig. 12 effects of noisy-Rician ($K = 2$) and noisy-Weibull ($V = 4$) faded R-channel on total error performance are shown. The performance under BSC with $r = 0.001$ case is also shown for a comparison purpose in Fig. 12. As in Figs. 9 and 10, it is also seen from both Figs. 11 and 12 that the total error probability initially decreases with increases in value of λ_n and increases next with further increase in value of λ_n. Similar behaviour is also observed in case of variation of p and M. It can be seen from both Figs. 11 and 12 that there exists an optimum value of λ_n for fixed values of p and M for which the total error probability is minimum. For example, in case of Hoyt ($q = 0.2$) fading channel (Fig. 11), the optimum value of λ_n is 25 for $p = 4$, $M = 1$, while it is 70 for $p = 4$, and $M = 3$. Operating the proposed IED-CSS system in noisy-Weibull faded R-channel environment provides the best performance as compared to operating the same system in other noisy-faded R-channel environments. The CSS with SC diversity ($M > 1$) outperforms the CSS without diversity ($M = 1$) under the same value of network and channel parameters.

Fig. 13 shows the effects of Hoyt (q), Rician (K), and Weibull (V) fading parameters on spectrum sensing performance in terms of total error probability. Different values of Hoyt fading parameter ($q = 0.25$, 0.5, and 1.0), Rician fading parameter ($K = 0$, 2, and 5), and Weibull fading parameter ($V = 2$, 4, and 6) are considered. The performance with $q = 1$, $K = 0$, and $V = 2$ corresponds to the performance with Rayleigh fading. S-channels are considered as noisy and Rayleigh faded, while R-channels are considered as noisy and (a) Hoyt (b) Rayleigh, (c) Rician and (d) Weibull faded channels. When fading parameters increase i.e. with reduction in severity of fading the total error probability decreases.

Table 4 shows comparison between IED-CSS and CED-CSS systems in terms of missed detection (Q_m), false alarm (Q_f) and total error probabilities ($Q_m + Q_f$) under OR-logic fusion for several cases of R-channels, and different values M and N. Two values of M namely 1 and 2; two values of N namely 1 and 3 are considered. The S-channel SNR, R-channel SNR and normalized detection thresholds are considered as 10 dB, 10 dB, and 30, respectively. The S-channel is considered as noisy and Rayleigh faded while R-channel is considered as several cases such as Ideal (noise less channel), BSC with fixed error probability $r = 0.001$, noisy-Hoyt with $q = 0.25$, noisy-Rayleigh, noisy-Rician with $K = 2$, and noisy-Weibull with $V = 4$. The Qm, Q_f and $Q_m + Q_f$ decreases for both the detectors when the number of CR users and number of antennas increase in all the cases of R-channels. It is seen that performance of IED-CSS system in faded R-channels outperforms the performance of CED-CSS system under same channel and network parameters. For example, in case of ideal R-channel and for $M = 2$, when N increases from 1 to 3, total error probability decreases by 23.70%, with CED-CSS system and 82.47% with IED-CSS system. Similarly, in case of fading (say Weibull, $V = 4$) and $M = 2$, we have found that the percentage (%) of decrease in total error probability is 23.50% with CED-CSS system and 79.47% with IED-CSS system when N increases from 1 to 3. This is obvious that the performance of IED-CSS as well as CED-CSS systems degrades with faded R-channel as compared to the same systems with both ideal and BSC R-channel cases. However, in many practical situations, R-channels may not be ideal or noisy (non-faded) channels. We also observe that performance of IED-CSS system (for $N = 3$) with SC diversity ($M = 2$) and without diversity ($M = 1$) is better than the performance with CED-CSS system in all the cases of R-channels. For example, Weibull faded channel and $N = 3$ case, when $M = 1$, we have found that the total error probability is 0.0781 with IED-CSS system and 0.8171 with CED-CSS system. The Q_m, Q_f and $Q_m + Q_f$ with IED-CSS system is less than the probabilities with CED-CSS system.

Table 4 Comparison between CED-CSS and IED-CSS.

R-channel	Values of M and N	Conventional detector ($p = 2$) based CSS			Improved detector ($p = 4$) based CSS		
		Q_m	Q_f	$Q_m + Q_f$	Q_m	Q_f	$Q_m + Q_f$
Ideal	$N = 1$, $M = 2$	0.8735	0.0000	0.8735	0.1538	0.0083	0.1621
	$N = 3$, $M = 2$	0.6664	0.0000	0.6664	0.0036	0.0248	0.0284
	$N = 3$, $M = 1$	0.8164	0.0000	0.8164	0.0603	0.0125	0.0728
BSC, $r = 0.001$	$N = 1$, $M = 2$	0.8727	0.0010	0.8737	0.1545	0.0093	0.1638
	$N = 3$, $M = 2$	0.6647	0.0030	0.6677	0.0037	0.0277	0.0314
	$N = 3$, $M = 1$	0.8173	0.0000	0.8173	0.0601	0.0130	0.0731
Hoyt, $q = 0.25$	$N = 1$, $M = 2$	0.8423	0.0400	0.8823	0.1829	0.0485	0.2314
	$N = 3$, $M = 2$	0.6506	0.0412	0.6918	0.0442	0.0649	0.1091
	$N = 3$, $M = 1$	0.7917	0.0411	0.8328	0.0955	0.0527	0.1482
Rayleigh	$N = 1$, $M = 2$	0.8527	0.0232	0.8759	0.1592	0.0318	0.1910
	$N = 3$, $M = 2$	0.6558	0.0235	0.6793	0.0262	0.0458	0.0720
	$N = 3$, $M = 1$	0.8006	0.0224	0.8230	0.0782	0.0343	0.1125
Rician, $K = 2$	$N = 1$, $M = 2$	0.8630	0.0118	0.8748	0.1627	0.0194	0.1821
	$N = 3$, $M = 2$	0.6622	0.0120	0.6742	0.0155	0.0366	0.0521
	$N = 3$, $M = 1$	0.8100	0.0116	0.8216	0.0717	0.0236	0.0958
Weibull, $V = 4$	$N = 1$, $M = 2$	0.8705	0.0030	0.8735	0.1553	0.0113	0.1666
	$N = 3$, $M = 2$	0.6653	0.0029	0.6682	0.0063	0.0279	0.0342
	$N = 3$, $M = 1$	0.8141	0.0030	0.8171	0.0631	0.0150	0.0781

6. Conclusions

We have investigated the performance of IED with multiple antennas based CSS in Rayleigh faded S-channels and several cases of R-channels such as BSC with a fixed error probability, Hoyt, Rayleigh, Rician and Weibull faded. Closed form analytical expressions of missed detection probability have been derived in AWGN and Rayleigh faded S-channel environments. Overall missed detection probability (Q_m) and total error probability ($Q_m + Q_f$) at the output of FC employing AND logic, majority logic, and OR logic fusion rules have been used to evaluate the performance of the network. Increase in cooperation among the CR users decreases the probability of missed detection and total error probability. The IED parameter and the number of antennas at each CR user have significant impact on total error performance. The optimum values of p and λ_n minimizing total error for different number of CR users and number of antennas in several cases of fading in R-channels has been estimated. The OR fusion rule outperforms both AND fusion rule and MAJORITY fusion rule at very low SNR range. The performance of IED-CSS in the presence of fading (Rician or Weibull) degrades as compared to the performance in BSC. Performance of CSS improves with increase in fading parameter (K) i.e. with reduction in severity of fading in case of Rician fading. The above study is useful in designing a cooperative based cognitive radio network in presence of various types of impairments in reporting channel.

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